The Society for engineering in agricultural, food, and biological systems

CSAE SCGR The Canadian Society for Engineering in Agricultural, Food, and Biological Systems

An ASAE/CSAE Meeting Presentation **Paper Number: 042196**

Complete Center Pivot Automation Using the Temperature-Time Threshold Method of Irrigation Scheduling.

R. Troy Peters, Ph.D.

USDA-ARS, P.O. Drawer 10, Bushland, TX 79012, tpeters@cprl.ars.usda.gov.

Steven R. Evett, Ph.D.

USDA-ARS, P.O. Drawer 10, Bushland, TX 79012, srevett@cprl.ars.usda.gov.

Written for presentation at the
2004 ASAE/CSAE Annual International Meeting
Sponsored by ASAE/CSAE
Fairmont Chateau Laurier, The Westin, Government Centre
Ottawa, Ontario, Canada
1 - 4 August 2004

Abstract. *It has been shown that the temperature-time threshold (TTT) method of automatic irrigation scheduling is a viable alternative to traditional soil water based irrigation scheduling in the Southern High Plains. The TTT method involves using infrared thermocouples (IRTCs) to remotely examine crop canopy temperatures over the course of a day. If a threshold canopy temperature is exceeded for a predetermined threshold time an irrigation event is scheduled. Applying this method using IRTCs mounted on self propelled irrigation systems such as center pivots or linear moves presents special challenges. First, it necessitates a method of estimating the diurnal canopy temperature dynamics using only a one-time-of-day canopy temperature measurement. Secondly, it requires a method of automatically collecting and analyzing the canopy temperature data and controlling the moving irrigation system based on the data analysis. A method of determining the diurnal canopy temperature curve using a one-time-of-day temperature measurement and a reference temperature curve was developed. The mean absolute error from calculated to observed was approximately 0.5° C from 0800 h to 2200 h. An array of 16 IRTCs were connected to a datalogger and mounted on a three tower center pivot. A separate array of IRTCs was located in stationary positions in the field and also connected to a datalogger. Two different spread spectrum*

(900 MHz) radios were connected to a desktop computer located nearby that queried both dataloggers, and got pivot status information and send commands to the center pivot control panel. Using scheduled data collection intervals, this computer was able to collect the data, analyze it, determine need for an irrigation event, and issue control commands thus completely automating the center pivot.

Keywords. Precision Irrigation, Center Pivot, Automation, Canopy Temperature, Infrared Thermometers, Canopy Temperatures

Introduction

An automated irrigation scheduling and control system that responds to stress indicators from the crop itself has the potential to lower crop management and labor requirements and to increase yields per unit of irrigation water. Burke (1993) and Burke and Oliver (1993) showed that plant enzymes operate most efficiently in a narrow temperature range termed the thermal kinetic window. Wanjura et al. (1992, 1995) demonstrated that the use of this window as a canopy temperature threshold could be used as a criterion for simplifying and automating irrigation scheduling. Upchurch et al. (1996) received U.S. patent no. 5,539,637 for an irrigation management system based on this optimal leaf temperature for enzyme activity and a climate dependant time threshold. This was termed the temperature-time-threshold (TTT) method of irrigation scheduling. With this method, for every minute that the canopy temperature exceeds the threshold temperature one minute is added to the daily total (fig. 1). If this daily total exceeds the time threshold at the end of the day, then an irrigation of a fixed depth is scheduled. Since humidity can limit evaporative cooling, minutes are not accrued if the wet bulb temperature is greater than the threshold temperature minus two degrees Celsius. Evett et al. (1996, 2000) demonstrated in drip irrigated plots that automatic irrigation using the TTT method was more responsive to plant stress and showed the potential to out-yield manual irrigation scheduling based on a 100% replenishment of crop water use as determined by neutron probe soil water content measurements.

The TTT irrigation scheduling method is easily automated with solid set systems such as drip irrigation where canopy temperatures can be measured in stationary positions in the field

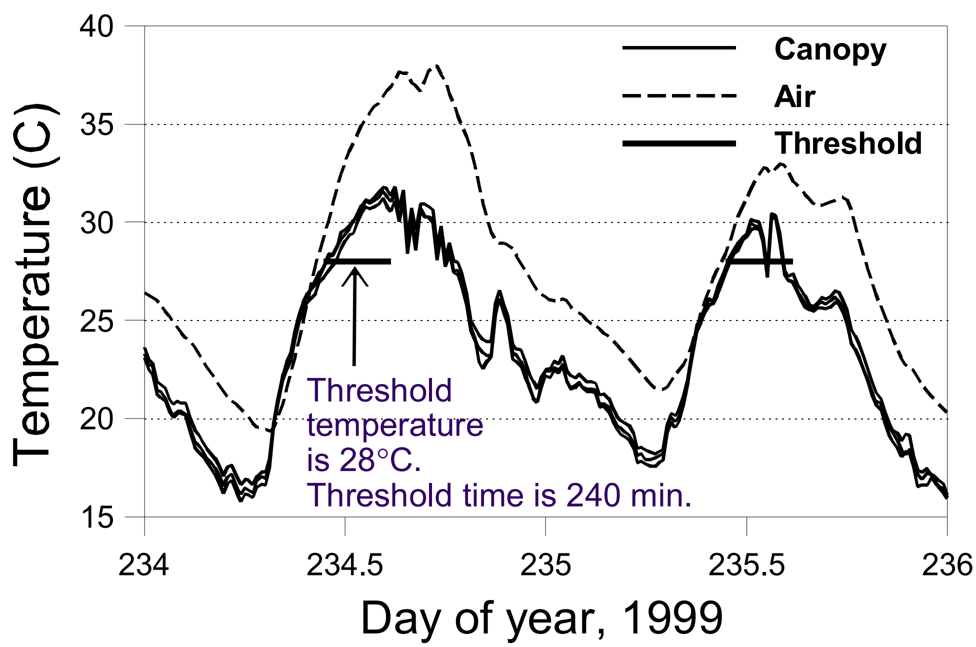

Figure 1. Canopy temperatures of three replicate plots on corn in 1999 (Evett et al, 2000) compared with air temperature. Also shown are horizontal bars drawn at the threshold temperature of 28 °C and over the length of the threshold time (240-min). Because the canopy was above the threshold temperature for more than the threshold time on day 234, irrigation occurred in the evening of that day, but not in the evening of day 235.

throughout the day. However, infrared radiation sensors mounted on self-propelled center pivots or linear move irrigation systems can provide only one-time-of-day canopy temperature measurements at each field location; and these measurements occur at uncertain times of day. The application of the TTT system of irrigation scheduling to specific locations under a center pivot or linear move irrigation system requires a method of determining diurnal canopy temperature dynamics at each location from these one-time-of-day canopy temperature measurements. It also requires a method of automatically collecting and analyzing the canopy temperature data and controlling the moving irrigation system based on the data analysis.

Unless a self-propelled irrigation system is moving dry (dead heading), once it is moving, an irrigation decision has already been made. However, the readings taken from a moving irrigation platform can serve as very useful feedback about the irrigation decision made, and about field conditions and problem areas. This feedback can be used to fine tune the irrigation scheduling process and provide a very useful data set for integration with precision irrigation applications.

The objectives of this study are to: (1) apply the TTT method of irrigation scheduling to a center pivot irrigation system with the infrared thermocouples mounted on the center pivot itself; (2) configure the center pivot so that it is automatically controlled according to the plant water needs as determined from the TTT method of irrigation scheduling; (3) compare the automatic TTT, center pivot irrigation scheduling to manually controlled irrigation based on neutron probe soil water content measurements in the same field.

Diurnal Canopy Temperature Determination

Extrapolating a diurnal canopy temperature curve from a one-time-of-day measurement requires an estimation of the canopy temperature dynamics due to changing environmental conditions. Several different models exist that can predict the dynamics of the crop canopy temperature as part of a soil-plant-atmosphere energy balance (e.g. Evett and Lascano, 1993). However, these models require as input detailed weather data as well as knowledge of soil-and plant-specific parameters that are neither readily available nor easy to measure. The most direct and simple way to determine how changing environmental conditions over a day affect canopy temperature dynamics is to measure canopy temperature in one stationary reference location. We hypothesized that canopy temperatures in other parts of a field, which may be under different stresses, could be modeled relative to this reference using one-time-of-day temperature measurements from those locations.

If pre-dawn canopy temperatures throughout the whole field (T_e; *e* for early) are assumed to be the same then:

$$T_{rmt} = T_e + \frac{(T_{rmt,t} - T_e)(T_{ref} - T_e)}{T_{ref,t} - T_e} \quad (1)$$

where (fig. 2)

T_{rmt} = calculated canopy temperature at the remote location (°C)

T_{ref} = canopy temperature from the reference location at the same time interval as T_{rmt} (°C)

$T_{rmt,t}$ = one-time-of-day canopy temperature measurement at the remote location at any daylight time t (°C)

$T_{ref,t}$ = measured reference temperature from the time that the remote temperature measurement was taken (t).

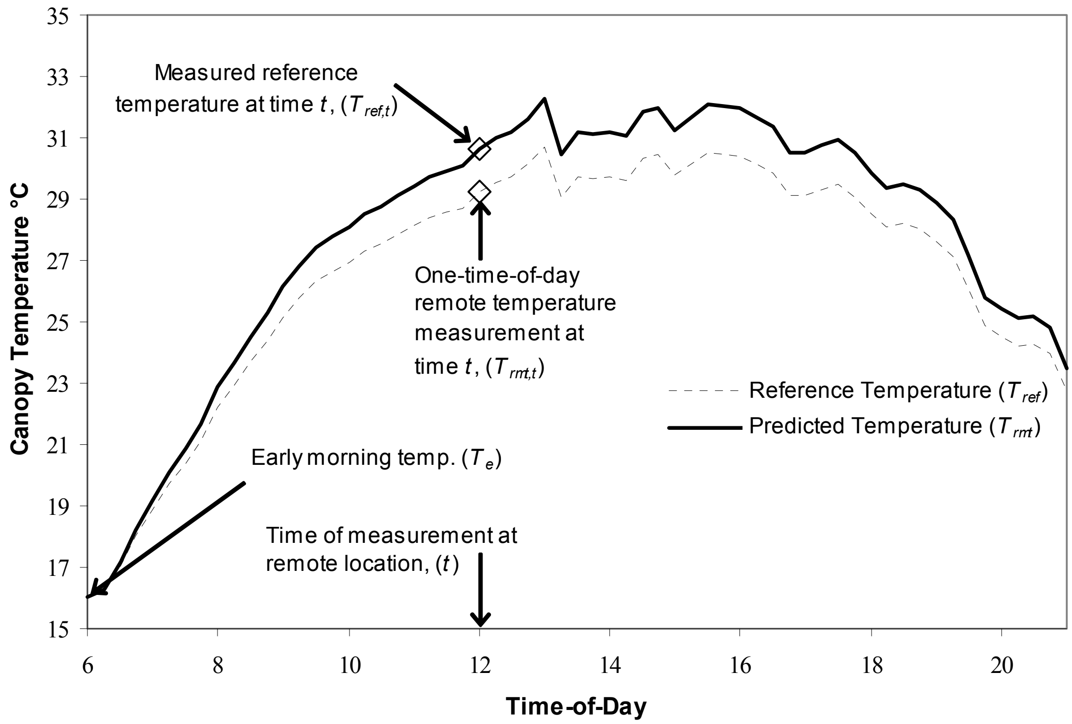

Figure 2. Diagram of the terms used in the scaled method (eq. 1). Time t might be any daylight time at which a canopy temperature ($T_{rmt,t}$) was measured at a remote location in the field. A contemporaneous temperature ($T_{ref,t}$) from the reference temperature data is then used in equation 1 along with the common pre-dawn minimum temperature (T_e) and each value in the reference temperature data (T_{ref}) to predict corresponding temperatures at the remote location throughout the daylight hours (T_{rmt}).

Equation 1 was tested with data from three separate years (1999, 2001 and 2002). Each year a different crop (corn, cotton and soybeans, respectively) was grown under drip irrigation studies done on the TTT method by Evett et al. (1996, 2000) from 1996 through 2002 at Bushland, Texas. In each of these studies, two different canopy temperature thresholds were used with two different time thresholds to create four automatic irrigation treatments as shown in table 1. Treatment plots were triply replicated resulting in twelve sets of canopy temperature data for each year and crop. Agronomic practices common in the region for high yield were applied.

Canopy temperature was measured with stationary infrared thermometers (model IRt/c.2-T-80, Exergen Corp., Watertown, MA)[1] and digitized with a data logger (model 21X , Campbell Scientific, Inc., Logan, UT) that also served to control flow to the 12 plots irrigated by canopy temperature control. One infrared thermometer (IRT) was allocated per plot, mounted on an adjustable mast one third of the distance from the south end of the plot, and adjusted to point down 45° from the horizontal and to point across the rows at 45° from north towards the east. Canopy temperature data were recorded in 1999 when the plots were planted to corn from day of year (DOY) 180 to 256. Canopy temperatures were recorded for cotton in 2001 from

[1] Mention of trade names or commercial products in this paper is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture

Table 1. Summary of the treatments used for each year and crop.

Year	Crop	Thresholds Temp (°C)	Thresholds Time (min)	Relative Irrigation
1999	Corn	28	240	Mid*
		28	160	Most
		30	160	Mid*
		30	240	Least
2001	Cotton	28	452	Mid*
		28	288	Most
		30	288	Mid*
		30	452	Least
2002	Soybean	27	256	Mid*
		27	171	Most
		29	171	Mid*
		29	256	Least

*Theoretical irrigation to meet crop needs as described in Evett et al. (1996, 2000).

DOY186 to 269, and for soybeans in 2002 from DOY 222 to 276. Each irrigation was 10 mm, which is equivalent to the crop's peak daily ET calculated from historical data. The four irrigation treatments resulted in a range of canopy temperature dynamics.

Linear correlations amongst diurnal canopy temperatures for all irrigation treatments were calculated. Among all of the various irrigation treatments and crops, the lowest obtained r^2 value was 0.96. The average of all the other r^2 values was 0.99. This shows a strong linearity between the dynamics in one treatment and the dynamics in another and supports the linear scaling equation (eq. 1). From the calculated temperature predictions, the mean absolute error for each 15-min time interval was calculated for all days in each season, and for each treatment (fig. 3). The mean absolute error between the predicted and actual temperatures from 0800 h to 1000 h was roughly 0.5 °C.

The total number of irrigations scheduled using the TTT irrigation scheduling method and the field-measured temperature data was compared with irrigations scheduled using the TTT method and diurnal canopy temperature curves predicted by equation 1 from one-time-of-day measurements. The magnitude of the maximum departure of the cumulative irrigation curve from the actual cumulative irrigation curve in figure 4 was 3.0 irrigations (30 mm) on DOY 256. These same statistics were calculated for every crop and treatment (table 2). The maximum end-of-year difference was an average of 4.8 irrigations for the 30/452 treatment for cotton using the scaled method. However, the mean of the end-of-year differences between actual and average predicted irrigations was 1.8 irrigations, or 18 mm of water.

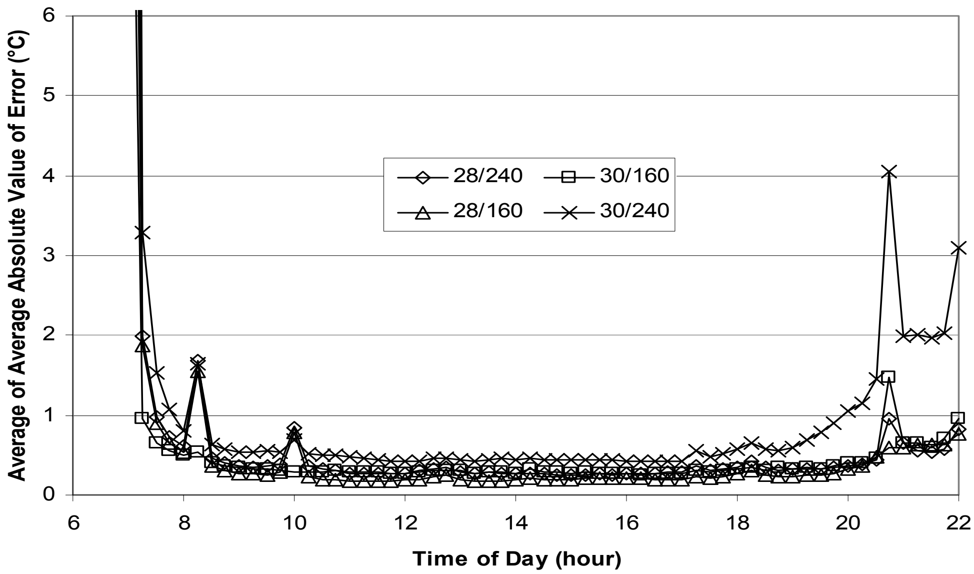

Figure 3. The average (across days) of the diurnal mean absolute error in temperatures predicted using the remote location temperature ($T_{rmt,t}$) at each time *t*. Results shown are from one plot from each treatment in the 1999 corn crop. The mean temperature of the 28° C threshold temperature, 160-min time threshold treatment was used as the reference.

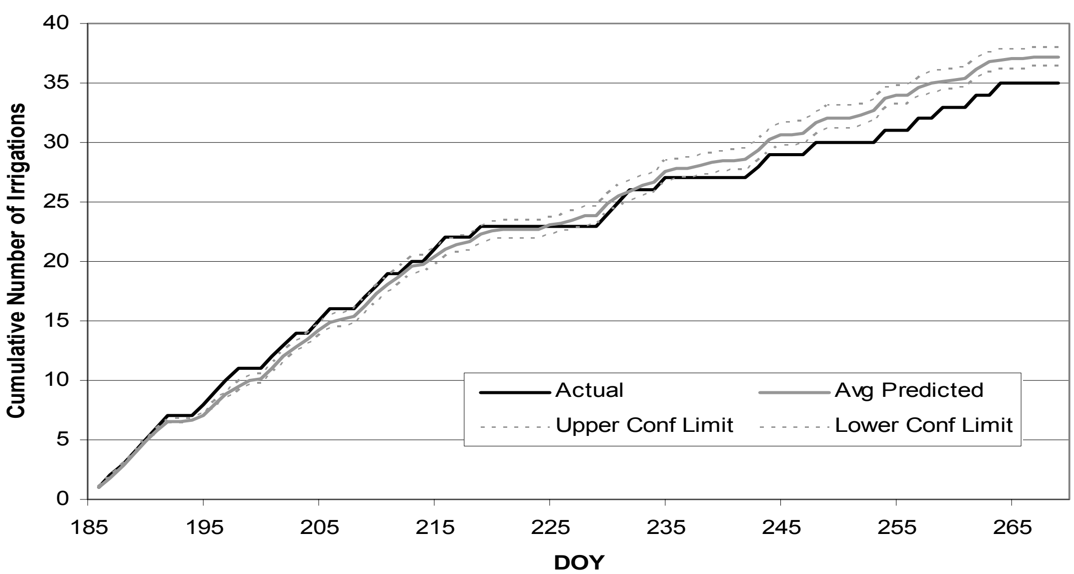

Figure 4. Comparison of the cumulative number of irrigations calculated using the TTT method and the field-measured canopy temperature data with that done using predicted (eq. 1) diurnal temperature dynamics. The predicted curve is from the mean irrigation signal predicted for that day using one-time-of-day temperature measurements at all times from 0815 h to 2200 h. The 95% confidence limits on this mean are also shown. Data are from the 2001 cotton crop 28° C temperature threshold, 452-min time threshold treatment.

Table 2. Magnitude of the end-of-year and maximum differences between the actual and predicted (using equation 1) number of irrigations over the irrigation season.

Year	Crop	Irrigation Treatment†	End-of-Year Difference	Maximum Difference
1999	Corn	28/240	0.6	0.9
		28/160	-1.4	-1.5
		30/240	-1.4	-1.4
		30/160	-3.0	-3.0
2001	Cotton	28/452	-2.2	-3.0
		28/288	-2.4	-2.4
		30/452	-4.8	-4.8
		30/288	2.6	2.6
2002	Soybeans	27/256	0.8	-0.9
		27/171	-1.7	-1.7
		29/256	-0.6	-1.4
		29/171	1.1	1.4

† The first number in each treatment code is the threshold temperature; the second number is the threshold time. For example, the code 28/240 indicates a 28°C threshold temperature and a 240-min threshold time (Evett et al., 1996, 2000).

These data show that equation 1 is a viable method for predicting the diurnal canopy temperature dynamics from a one-time-of-day measurement using a reference temperature during daylight hours. At night, the closest approximation to canopy temperature is simply the reference temperature. This method enables the evaluation of the TTT method for irrigation scheduling in fields underneath a self propelled irrigation platform.

Pivot Instrumentation and Control

The experiment site was a three-tower, 127 m long research center pivot located at the USDA-ARS Conservation and Production Research Laboratory in Bushland, Texas (fig. 5). Only half of the field was used. Soybeans were planted in concentric circles out from the center point. Agronomic practices common in the region for high yields were applied. Four different water level treatments were applied radially out from the center point (100%, 66% and 33% of projected irrigation needs, and a dry-land, or no irrigation treatment). Each drop was pressure regulated to 6 psi. The irrigation level was controlled by nozzle sizes as appropriate. Drops were spaced every other row (1.52 m) and irrigated with low energy precision application (LEPA) drag socks. The furrows were dammed/diked to limit water movement in the furrows. Two replications of each of the irrigation level treatments were applied in a randomized block pattern with the second tower wheel track serving as the block separation line. Within the half pivot there were three replications each of an automatically controlled (via the TTT method) treatment, and a treatment that was manually scheduled (using soil water deficiency as determined by neutron probe soil moisture content readings). These treatments were applied in wedge shapes alternatively to block for differing soil types underneath the pivot. Two additional

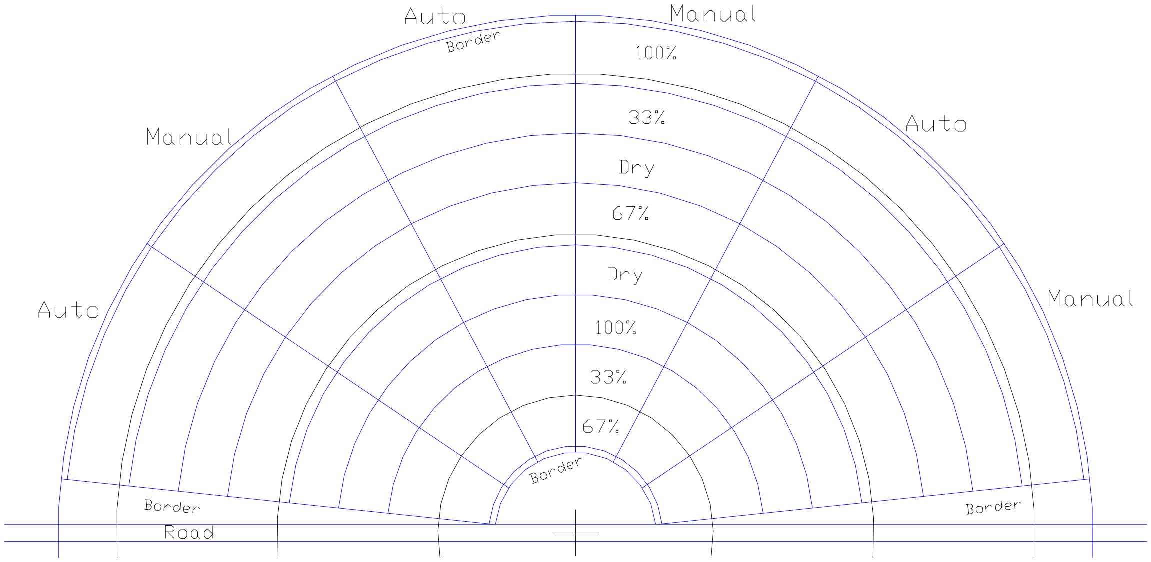

Figure 5. Automatic center pivot irrigation experiment plot plan.

rows of soybeans are planted around the outside and inside edges of the pivot to help minimize border effects.

The pivot movement and positioning were controlled remotely by a computer located in a nearby building which communicated through two different 900 MHz radio frequency (RF) radios (fig. 6). One radio was part of a center pivot remote control system ("Base Station") produced by Valmont Industries. This radio communicated with the pivot through a second radio mounted at the pivot center point and allowed status checks and control commands to be sent to the

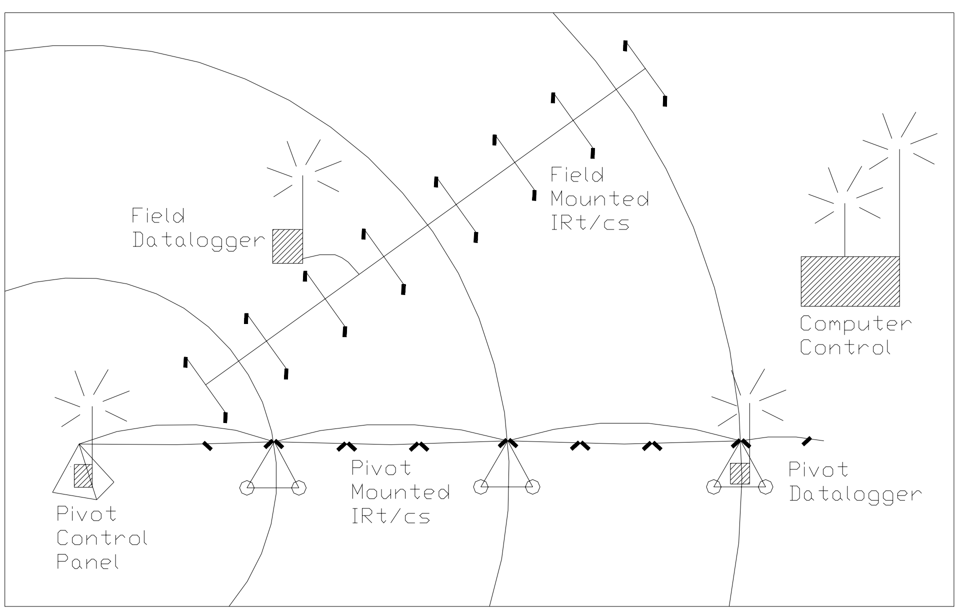

Figure 6. Automatic center pivot control set-up.

pivot control panel. The second system consisted of a Campbell Scientific RF400 radio which communicated to similar radios connected to a datalogger mounted on the pivot and a separate datalogger in the field.

The center pivot-mounted datalogger collected data from 16 different infrared thermocouples (IRTC) (Exergen model IRt/c.JR-10) which were attached to the trusses of the pivot (fig. 6). They were mounted on the leading side of the pivot and the pivot was only allowed to irrigate in one direction so that the sensors would not view wet canopy. The IRTCs were narrow field of view (ratio of distance to view spot size was 10:1) and were oriented so that they pointed parallel to the center pivot arm (perpendicular to crop rows) towards a spot in the middle of each concentric irrigation treatment plot. In order to minimize sensor angle related effects, a separate IRTC was aimed at approximately the same spot from the other direction. The average of these two readings for each plot was used. Wanjura et. al. (1995) reported that canopy temperatures differed less than 0.5° C when measured by either one sensor in the nadir position, or two sensors pointed at the row from opposite directions. Using two sensors in the indicated positions allowed earlier use of the irrigation scheduling techniques since at high angles less of the soil between rows was in the sensor field-of-view. This also allowed larger amounts of the crop canopy to be seen by the sensors and averaged into the reading. Problems with misalignment of the IRTCs over the rows as the pivot moved around the field were also avoided. The IRTCs on the pivot were connected to a multiplexer (Campbell Scientific AM25T) at the second tower and the results conveyed to the datalogger (Campbell Scientific CR10X) at the third and last tower. Each of the IRTCs measured the canopy temperature on 10 second intervals and the one minute averages were logged.

A separate array of 16 IRTCs (Exergen model IRt/c.2-T-80) were mounted in stationary locations and connected to a separate datalogger in the field. Each IRTC was mounted in the nadir position over the crop row close enough to the canopy so that soil was not included in the field-of-view. These IRTCs were adjusted up with the changing height of the canopy. One IRTC was mounted in each irrigation level of both the automatic and manual treatments. These IRTCs were similarly connected through a multiplexer (Campbell Scientific AM25T) and to a datalogger (Campbell Scientific CR21X). The datalogger logged the five minute averages of each of the IRTC readings collected on 10 second intervals.

Each IRTC was separately calibrated using a black body (Omega Black Point, model BB701) before the season began. A second order polynomial was fitted to the results of the calibration and each IRTC was individually corrected by the data analysis software running on the control computer in the nearby building.

A differentially corrected GPS receiver (Garmin, model 16 HVS) was mounted on the overhang past the end tower. The output NMEA (National Marine Electronics Association) sentences using the RS-232 protocol were read by the pivot-mounted datalogger. The position was read in latitude and longitude and converted to an X-Y position in meters relative to the pivot center point using algorithms given by Carlson (2003). However, the positioning was too unstable (standard deviation nearly 4 times as great as that of the resolver) and because the pivot was short, the stated 3-5 meter accuracy of this receiver was inadequate for the precision of control required (1.4° – 2.3° error in pivot angle position). However, the position as reported by the pivot resolver was found to be as much as five degrees off (yaw). Therefore the resolver angle was mathematically corrected using a sinusoidal wave form fitted to the error using the least square error method. This resulted in the correction equation:

$$P_a = P_r + 3.7\sin\left[\left(P_r - 5.1\right)\frac{\pi}{180}\right] - 3.7 \qquad (2)$$

where the sine is calculated in radians and

P_a = actual position of the center pivot (degrees)

P_r = position as reported by the resolver (degrees).

During an automatic irrigation event the pivot stopped at the edge of the treatment, paused 10 minutes to drain, and then ran dry over the manual irrigation treatment. It would then pressure up again for the next automatic irrigation treatment and continued on in this fashion until all of the automatic irrigation segments were irrigated. An application depth of 20mm was applied at each automatic irrigation event. This was equivalent to the maximum, two-day evapotranspiration rate for the region during the hot summer months. After irrigating the last automatic plot the pivot continued on around dry to its starting point. During a manual irrigation event the pivot performed similarly except it would irrigate only the manual irrigation treatments at a manually set application depth required to replenish soil water content and prevent crop stress for the 100% treatments. This soil water deficit was determined by weekly neutron probe readings in the 100% manual irrigation treatments. In order to both manually and automatically control the same pivot, automatic irrigations were only allowed on even days of year, and manual irrigations were only allowed on odd days of year.

The central control computer was programmed to call the pivot-mounted datalogger and the pivot control panel every minute to retrieve status reports. Custom developed software was written in Visual Basic that tested whether the pivot had crossed a plot boundary. If it had, new instructions were sent to the pivot depending on its location and the program (automatic or manual) that it was running at the time.

The field datalogger was polled only once a day soon after midnight. At this time the previous day's data was analyzed to determine the next day's strategy. If the pivot did not move during the previous day, the temperature curve collected by the pivot mounted IRTCs from where the pivot sat all day was used to determine whether an irrigation was required. If the pivot *did* move during the previous day then a subroutine was called that scaled one time-of-day temperature measurements and made decisions based on the results. The two canopy temperature measurements from the field-mounted IRTCs in the 100%, automatic treatments were averaged together and used as the reference curve for scaling the one time-of-day measurement into a diurnal curve (equation 1). The field was divided up into four-degree wedge shapes and readings taken from within each of these wedge shapes were averaged together for each radial plot. Three different files were created containing values for each of the 8 plots (4 irrigation levels * 2 reps) in each of these four-degree wedge shapes. These files were: the average remote temperature (since many readings may have been taken in each four-degree wedge), the number of minutes the scaled curve was above the temperature threshold, and the temperature from each remote location scaled to 12:00 noon. Each of these files was used for information purposes only. They were used to evaluate each irrigation decision and to evaluate the spatially variable crop conditions. This type of information could be used in future experiments for precision agricultural decision making.

Conclusion

In an overview of current precision irrigation technologies Evans et. al. (2000) concluded that in order for site specific irrigation to be practical on a large scale, inexpensive real-time sensing of the soil and/or plant status integrated with communications networks and control and decision support systems needed to be developed. The methods presented here make significant headway towards that goal. A method for modeling canopy temperature dynamics using a one time-of-day temperature measurement and a reference curve was presented and tested. A three tower experimental center pivot was outfitted with communications and control hardware for automatic control and the methods were presented here.

Most precision irrigation technology is too costly and complicated to be readily applicable by average farmers. However the costs and simplicity of the methods similar to what was presented here may become attractive to producers. Especially since it has the potential to both simplify management while increasing yields and/or decreasing water related costs.

Acknowledgements

We would like to thank Dean Evans at Coastal Plain Soil, Water and Plant Conservation Research Unit of the ARS-USDA in Florence, SC for sharing his code for communicating with the center pivot which was used in a separate experiment (Evans, 2000). We also gratefully acknowledge the help of Bryce Ruthardt from the USDA-ARS Bushland, TX research station in managing the data collection and setting up the hardware for these experiments.

References

Burke, J.J. 1993. Thermal kinetic windows of plant enzymes. In *Biotechnology for Aridland Plants, Proc. International Symp. IC² Institute.* Mabry, T.J., Nguyen, H.T., Dixon, R.A., Bonness, M.S. (eds.) The University of Texas, Austin. (pp. 73-82.)

Burke, J.J., and M.J. Oliver. 1993. Optimal thermal environments for plant metabolic processes (Cucumis sativus L.): Light-harvesting chlorophyll a/b pigment-protein complex of photosystem II and seedling establishment in cucumber. *Plant Phys.* 102(1):295-302

Carlson, C.G. 2004. What do latitude and longitude, readings from a GPS receiver mean? Available at: http://www.abs.sdstate.edu/abs/precisionfarm/EARTHMO1.html 3/10/2004. Accessed 28 October 2003.

Evans, D.E. 2000. Spatial Canopy Temperature Measurements Using Center Pivot Mounted IRTS. In *Proc. 5th International Conf. on Precision Agriculture*, CD-ROM. July 16-19. Bloomington, MN.

Evans, R.G. 2000. Controls for Precision Irrigation with Self-Propelled Systems. In *Proc. of the 4th Decennial National Irrigation Symposium*. Robert G. Evans, Brian L. Benham, and Todd P. Trooien (eds.) November 14-16, Phoenix, AZ.

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 1996. Canopy temperature based automatic irrigation control. In *Proc. International Conf. Evapotranspiration and Irrig. Scheduling*. C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.). November 3-6, 1996, San Antonio, TX. (pp. 207-213)

Evett, S.R., T.A. Howell, A.D. Schneider, D.R. Upchurch, and D.F. Wanjura. 2000. Automatic drip irrigation of corn and soybean. In *Proc. of the 4th Decennial National Irrigation Symp*. Robert G. Evans, Brian L. Benham, and Todd P. Trooien (eds.). November 14-16, Phoenix, AZ. (pp. 401-408)

Evett, S.R., and R.J. Lascano. 1993. ENWATBAL.BAS: A mechanistic evapotranspiration model written in compiled BASIC. *Agron. J.* 85(3):763-772.

Upchurch, D.R., Wanjura, D.F., Burke, J.J. and Mahan, J.R. 1996. Biologically-identified optimal temperature interactive console (BIOTIC) for managing irrigation. U.S. Patent No. 5539637.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1992. Automated irrigation based on threshold canopy temperature. *Trans. ASAE* 35(1):153-159.

Wanjura, D.F., D.R. Upchurch, and J.R. Mahan. 1995. Control of irrigation scheduling using temperature-time thresholds. *Trans. ASAE* 38(2):403-409.